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EXPERIMENTAL DETERMINATION OF THE COEFFICIENTS OF THE

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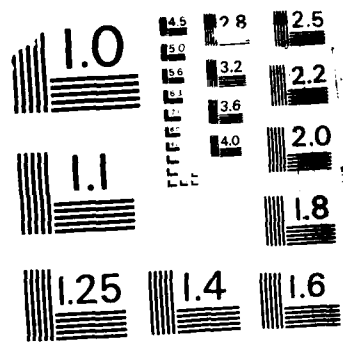
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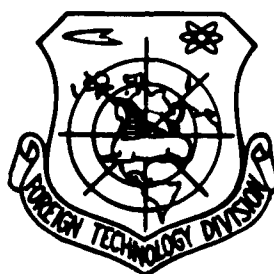
FOREIGN TECHNOLOGY DIVISION



EXPERIMENTAL DETERMINATION OF THE COEFFICIENTS OF THE HYDRAULIC RESISTANCE
OF APERTURES IN THE ROTARY DISKS

by

I.T. Shvets, Ye. P. Dyban, et al.



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FTD-ID(RS)T-1334-87

22 January 1988

MICROFICHE NR: FTD-88-C-000111

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English pages: 23

Source: Izvestiya Vysshikh Uchebnykh Zavedeniy
Energetika, Nr. 3, March 1960, pp. 89-99

Country of origin: USSR

This document is a machine translation.

Input by: Vicky L. Tipton

Merged by: Eva R. Johnson

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	<i>А а</i>	A, a	Р р	<i>Р р</i>	R, r
Б б	<i>Б б</i>	B, b	С с	<i>С с</i>	S, s
В в	<i>В в</i>	V, v	Т т	<i>Т т</i>	T, t
Г г	<i>Г г</i>	G, g	У у	<i>У у</i>	U, u
Д д	<i>Д д</i>	D, d	Ф ф	<i>Ф ф</i>	F, f
Е е	<i>Е е</i>	Ye, ye; E, e*	Х х	<i>Х х</i>	Kh, kh
Ж ж	<i>Ж ж</i>	Zh, zh	Ц ц	<i>Ц ц</i>	Ts, ts
З з	<i>З з</i>	Z, z	Ч ч	<i>Ч ч</i>	Ch, ch
И и	<i>И и</i>	I, i	Ш ш	<i>Ш ш</i>	Sh, sh
Й й	<i>Й й</i>	Y, y	Щ щ	<i>Щ щ</i>	Shch, shch
К к	<i>К к</i>	K, k	Ъ ъ	<i>Ъ ъ</i>	"
Л л	<i>Л л</i>	L, l	Ы ы	<i>Ы ы</i>	Y, y
М м	<i>М м</i>	M, m	Ь ь	<i>Ь ь</i>	'
Н н	<i>Н н</i>	N, n	Э э	<i>Э э</i>	E, e
О о	<i>О о</i>	O, o	Ю ю	<i>Ю ю</i>	Yu, yu
П п	<i>П п</i>	P, p	Я я	<i>Я я</i>	Ya, ya

*ye initially, after vowels, and after Ё, Ъ; e elsewhere.
When written as ё in Russian, transliterate as yě or ě.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	\sinh^{-1}
cos	cos	ch	cosh	arc ch	\cosh^{-1}
tg	tan	th	tanh	arc th	\tanh^{-1}
ctg	cot	cth	coth	arc cth	\coth^{-1}
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian English

rot curl
lg log

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EXPERIMENTAL DETERMINATION OF THE COEFFICIENTS OF THE HYDRAULIC
RESISTANCE OF APERTURES IN THE ROTARY DISKS.

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Institute of the thermal-power engineering of AS UkSSR.

During design and investigation of turbomachines need for
calculation of flow of gas (usually air or of vapor) through
openings/apertures, situated on certain radius of rotary disk,
frequently appears.

Thus, for example, during calculation of cooling multiple-plate
rotors of gas turbines it is necessary to determine value of drop/jump
in pressure on disk, which ensures course through openings/apertures
of prescribed/assigned quantity of air coolant.

Analogous task appears during calculation of cooling disk by
blasting through shanks of rotor blades. During the determination of
the axial force, which appears in the active step/stage of turbine,
the account of the overflows of the vapor through the discharging
openings/apertures of disks is produced.

For all these calculations it is necessary to possess data about value of hydraulic resistance or coefficient of expenditure/consumption through rotating openings/apertures.

By coefficient of flow rate is understood ratio of real gas flow through opening/aperture G to flow rate during isentropic flow G_0 ,

$$\mu = \frac{G}{G_0}. \quad (1)$$

By coefficient of hydraulic resistance it is customary to assume ratio of loss of pressure Δp to velocity head in cross section

$$\zeta = \frac{2\Delta p}{\rho c^2} \quad (2)$$

in question.

Since gas flow during isentropic flow is equal to

$$G_0 = F\gamma C_0 = F\gamma \sqrt{\frac{2\Delta p}{\rho}}, \quad (3)$$

but real flow rate through opening/aperture is determined by equation

$$G = F\gamma C = F\gamma \sqrt{\frac{2\Delta p}{\rho}}, \quad (4)$$

the between coefficient of hydraulic resistance and coefficient of flow rate exists relationship/ratio

$$\mu = \frac{1}{\sqrt{\zeta}}. \quad (5)$$

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Examining physical picture of flow of gas through opening/aperture of finite length arranged/located in rotary disk, it

is necessary to keep in mind that flow conditions is determined by series/row of different factors, moreover effect of part from these factors becomes apparent during flow of gas through fixed opening/aperture, and part of factors appears during rotation.

In general case on conditions of course of gas through opening/aperture they have effect:

- a) geometric form and sizes/dimensions of opening/aperture.
- b) configuration of intake and trailing edges.
- c) state of bore surfaces.
- d) presence of walls (shields) at entry and flow discharge from opening/aperture.

During rotation of disk to flow through openings/apertures, situated on certain radius, additionally have effect following factors:

- a) change of conditions of intake into openings/apertures, in connection with change in direction of gas velocity in cavity before disk.
- b) presence of moving medium at output/yield from opening/aperture, which causes change in conditions of escape of flow from openings/apertures.

c) emergence during rotation of disk of centrifugal efforts/forces, which change conditions for flow in opening/aperture.

Combined effect of factors enumerated above considerably complicates process, that it does not make it possible to describe by its system of mathematical equations and it requires therefore for determining laws governing this phenomenon of conducting special experimental investigations.

Careful analysis of results of studies carried out up to now of air flow through openings/apertures in rotary disks shows that this question is still very distant from its complete permission/resolution, but available in the literature data are very contradictory and do not give possibility to conduct substantiated calculation of hydraulic resistance of cooling system of rotating rotor.

Taking into account that presented, authors carried out in Institute of thermal-power engineering of AS UkSSR experimental investigation of rotational effect to hydraulic resistance of separate elements of cooling system of rotors of gas turbines. Experiments were conducted on the installation, whose schematic was given in Fig. 1.

air flow through rotating openings/apertures was studied in disks with diameter of 300 mm, had on radius 102.5 mm of 8

openings/apertures for interchangeable sleeves with channels of different sizes/dimensions and forms. Sleeves were fastened in the disk by special ring lock. A change in the number of revolutions of rotor was accomplished/realized by a system of three series-connected reducers, which ensure the maximum speed of rotation to 11550 r/min. The investigated range of change in the peripheral speed sufficiently fully encompasses working conditions of the steps/stages of turbine under the actual conditions.

Experimental disk was included in housing; clearance between disk and housing in axial direction was approximately 90 mm. To avoid flows, besides the openings/apertures on the periphery of disk, the packing/seal, which consisted of two series/rows of combs, was prepared. Between these series/rows the chamber/camera, connected through the branch connection with the atmosphere, was arranged/located. By the flow-rate control of air through branch pipes in the chamber/camera was supported the pressure, equal to pressure in the cavity after the disk, by which were eliminated the flows through the second series/row of packings/seals. Measurement of the air flow rate was produced at the output/yield from the experimental installation.

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For measuring of temperatures, flow rates and air pressure conventional, standard equipment was used. The measurement of complete air pressure before and after disk was carried out by the

total pressure tubes, established/installed at a distance of 30 mm from the lateral surface of disk on a radius of the openings/apertures being investigated. In connection with this that the torsion of the flow of rotary disk changes in the dependence on the air flow rate, in experiments the total pressure tubes, low-sensitivity are used to the angle of the inleakage of flow.

Fig. 1a gives absolute change in pressure (braking (in mm H₂O) in dependence on downwash angle, measured by used in experiments total pressure tube.

Results of calibration show that with value of angles of $\geq 45^\circ$ nozzle, whose construction/design is also given in Fig. 1a, remains virtually insensitive to angle of inleakage of flow.

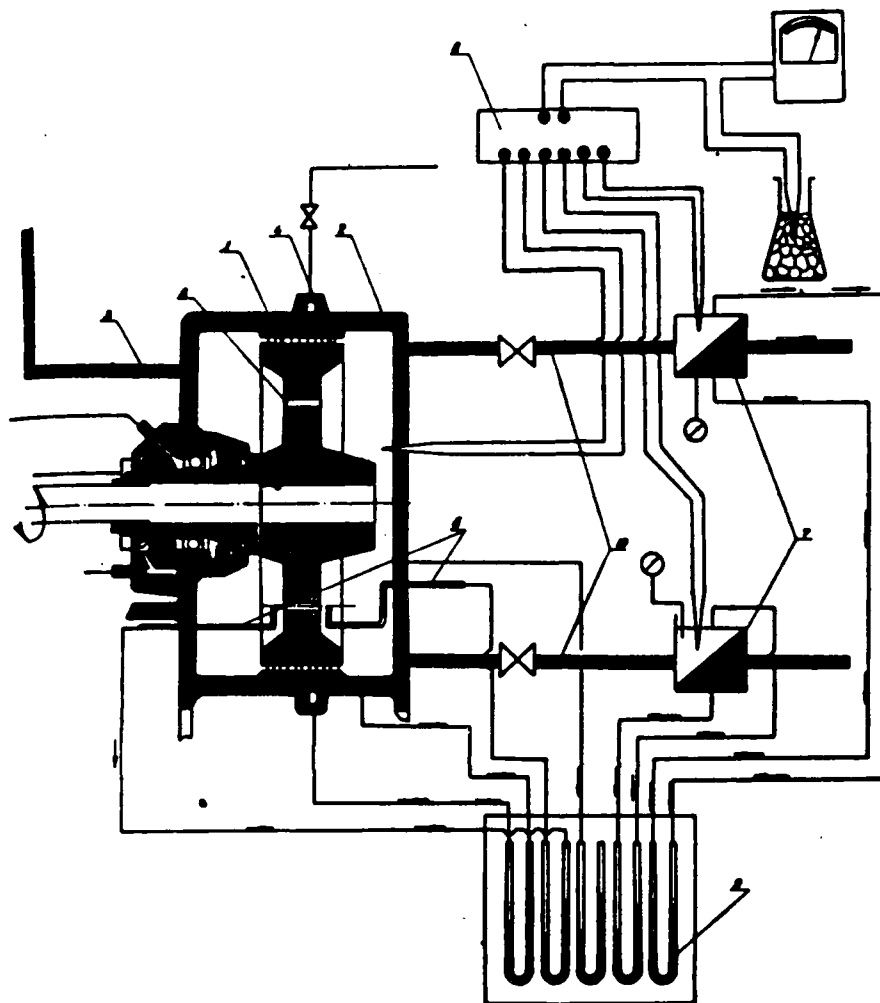


Fig. 1. Schematic of experimental installation: 1 - turbine disk, 2 - housing, 3 - intake pipe, 4 - labyrinth gland, 5 - interchangeable sleeves, 6 - total pressure tube, 7 - measuring diaphragm, 8 - measuring unit of temperature, 9 - measuring unit of pressure, 10 - exhaust pipe.

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Error analysis carried out on the basis of standard methods in

measurements showed that probable relative error in determination of value of coefficient of hydraulic resistance composes 1.5-2.5%, while those of coefficient of flow rate - 1.20 - 1.35%.

PROCEDURE OF EXPERIMENTAL STUDY.

In cooling systems of gas turbines, and especially in discharging openings/apertures of active steps/stages, speed of flow does not exceed 0.3 m/s, that compressibility effect of medium makes it possible not to consider.

Since temperature of air in our experiments did not exceed 310° abc, . were accepted measure for that so that speed of flow in openings/apertures would not exceed 100 m/s.

Increase in hydraulic resistance of opening/aperture during rotation of disk is caused by fact that vector of relative speed of flow is directed at angle toward axis/axle of opening/aperture. Therefore the angle between the direction of relative speed and the axis/axle of the opening/aperture must be the parameter, which characterizes a change in the conditions of flowing the medium through the openings/apertures in the disk during the rotation, :

$$K = \operatorname{tg} \varphi = \frac{u}{c}, \quad (6)$$

where u - peripheral speed on the axis/axle of opening/aperture.

c - mean flow rate in opening/aperture.

It is possible to easily show that parameter K is proportional to Strouhal's criterion

$$Sh = \frac{G}{\alpha} = \frac{1}{r} \cdot \frac{u}{c} \cdot \frac{d}{R}. \quad (7)$$

During calculation of hydraulic resistance of cooling system of rotor of gas turbine flow rate of air coolant is usually given one, and it is necessary to determine pressure differential, which ensures its overflowing through openings/apertures in rotary disk. Since absolute pressure at the output/yield from the opening/aperture in this case is known, the determination of the mean flow rate and parameter K does not present difficulties. From this point of view the representation of experimental data in the form of dependence $\mu=f(K)$ or $\xi f(K)$ is most advisable.

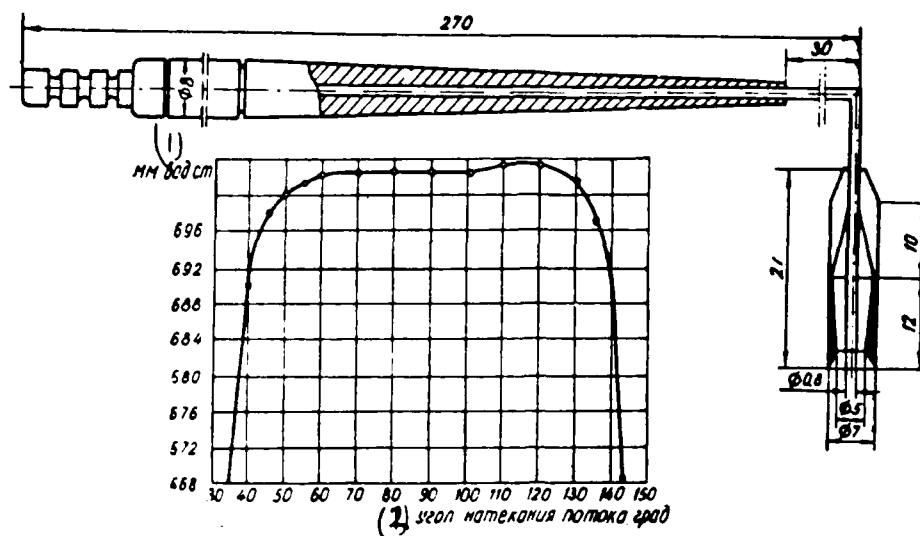


Fig. 1a.

Key: (1). baud cm. (2. angle of inleakage of flow deg.

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During calculation of flows through discharging openings/apertures in disks of active steps/stages given one is pressure differential, which impedes determination of mean flow rate in opening/aperture. In this case is more expedient to select as that determining the speed of isentropic outflow from the opening/aperture

$$C_0 = \sqrt{\frac{2\Delta p}{\rho}} \quad (8)$$

and to represent experimental data in the form of dependences $\mu=f(K_0)$ or $\xi=f(K_0)$, where

$$K_0 = \frac{u}{C_0}. \quad (9)$$

It is obvious that between both parameters there is dependence

$$K_0 = \mu \cdot K. \quad (10)$$

Experimental data, obtained with accomplishing of present study are represented as in the form of function from parameter K , so also from parameter K_0 , which makes it possible most simply to utilize them with computing cooling, also, during determination of axial forces.

RESULTS OF EXPERIMENTAL INVESTIGATION.

As has already been indicated, target of present investigation was determination of dependence of coefficients of flow rate and hydraulic resistance on:

- a) peripheral speed of disk at diameter of openings/apertures.
- b) relative depth of openings/apertures.
- c) configuration of entering edges.
- d) configuration of trailing edges.
- e) form of openings/apertures.

For studying effect of factors indicated on characteristics of air flow through openings/apertures in rotary disks it was carried out four sets of experiments. The cylindrical openings/apertures, which were being investigated in the first set of experiments, had sharp/acute intake and trailing edge, constant length (24.15 mm) and

following diameters: 4.0; 5.3; 6.5; 8.0; 10.0; 11.5; 13.3; 14.3; 20.0; 25.0 mm, which corresponds to a change in the relative depth l/d from 6.04 to 0.96 and encompasses entire possible in the gas turbines range of the sizes/dimensions of openings/apertures for supplying the air coolant.

Setup experiments, carried out with fixed disk showed that, in spite of taken measures, during manufacture of interchangeable sleeves occurred certain blunting of intake edges and disagreement in value of initial drag coefficient. For eliminating the effect of this phenomenon the results of experiments are processed in the form of the dependence of the ratio of the coefficient of flow rate μ with this K or K_0 to the value of the coefficient of the flow rate μ_0 of this opening/aperture with the fixed disk (Fig. 2.3).

Directly from analysis of experimental data, given in Fig. 2 and 3, it is evident that during rotation of disk coefficient of flow rate continuously decreases. In the investigated range of ratios l/d the effect of the relative depth of opening/aperture proved to be insignificant.

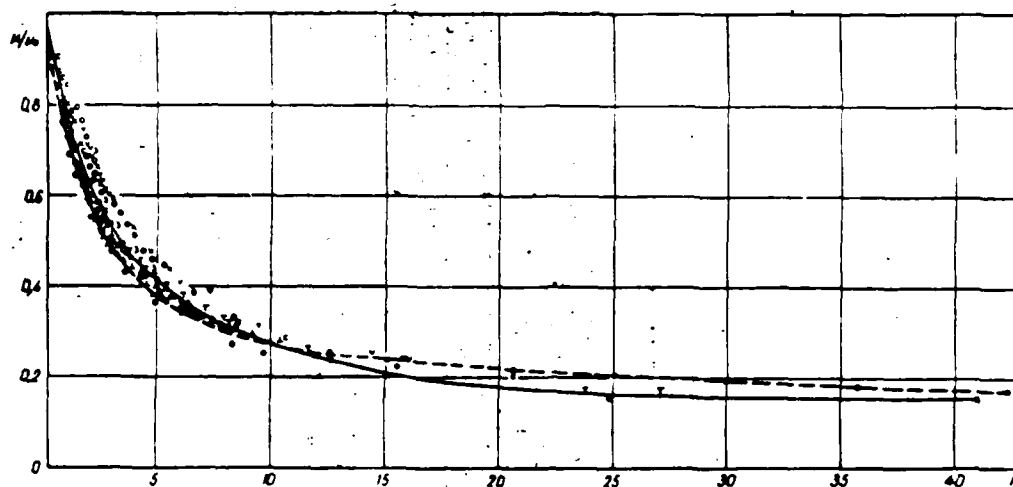
With neglect of effect indicated dependence of coefficient of flow rate of openings/apertures with sharp edge on rotation of disk can be described by equation

$$\mu = \frac{\mu_0}{1 - 0.16 K_0 + 0.43 K_0^2 - 0.05 K_0^3} \quad (11)$$

or

$$\mu = \frac{\mu_0}{1 + 0.3 K - 0.004 K^2} \quad (11a)$$

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Fig. 2. Rotational effect to value of coefficient of flow rate μ

(sharp intake and trailing edge). Diameter of the openings/apertures:

 $\times - d = 4, \circ - d = 5.3, \vee - d = 6.5, c - d = 8, r - d = 10, \square - d = 11.5, \bullet - d = 12.6, \triangle - d = 13.5, \odot - d = 14.3$
 $\wedge - d = 16.7, \perp - d = 20, \text{---} - d = 20.6$
 $\odot - \odot - \odot$ according to data [2].

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Analogous dependences for determining drag coefficient of entry and output/yield can be represented in the form

$$\xi = \frac{1}{\xi_0} (1 + 0,32 K_0 + 0,89 K_0^2 + 0,037 K_0^3 + 0,17 K_0^4 - 0,043 K_0^5 + 0,025 K_0^6) \quad (12)$$

and

$$\xi = \frac{1}{\xi_0} (1 + 0,6 K + 0,081 K^2 - 0,0024 K^3 + 0,000016 K^4). \quad (12a)$$

Character obtained in our experiments of dependence of value of coefficient of flow rate from parameters K and K_0 , coincides sufficiently well with results of experiments, carried out in MEI with relatively larger values of axial clearance between disk and housing [2].

Absolute values of coefficients of flow rate, determined as a result of present investigation, somewhat higher (sthene 10-15%), than according to data [2]. It is possible to assume that this disagreement is caused, on one hand, considerably by the larger value of the axial clearance between the disk and the housing from the side of intake, on the other, by presence in installation of the institute of the thermal-power engineering of the closed chamber/camera from exit side from the opening/aperture. It is possible to also assume

that certain torsion of flow appearing in this chamber/camera leads to an increase in the total pressure at the output/yield from the opening/aperture.

On the basis of that presented it is possible to make conclusion that empirical relationships/ratios proposed in the present work for determining value of coefficients of flow rate and hydraulic resistance of rotating openings/apertures must be used only for conditions, similar to those, which occurred during given experiments (relative axial clearance at output/yield of more than than 1.5, closed chamber/camera at output/yield).

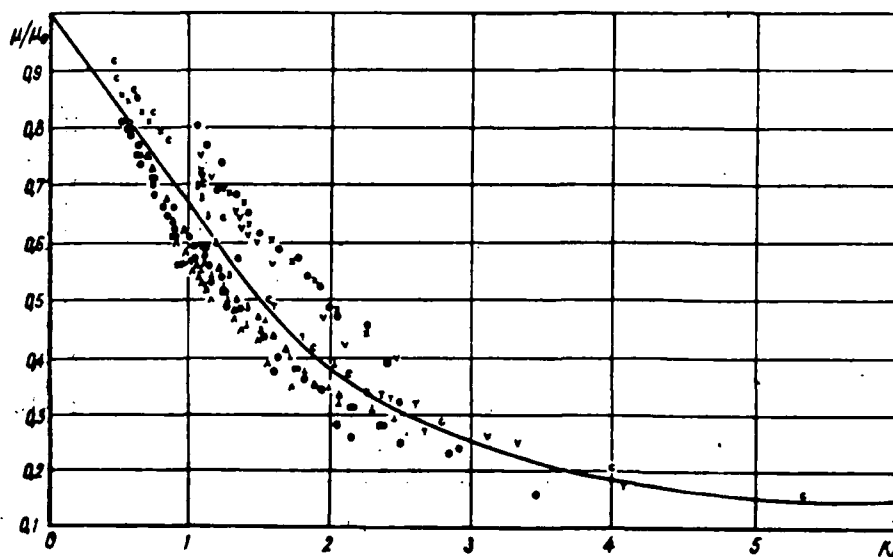


Fig. 3. Rotational effect to value of coefficient of flow rate μ (sharp intake and trailing edge). The designations of points are the same as in Fig. 2.

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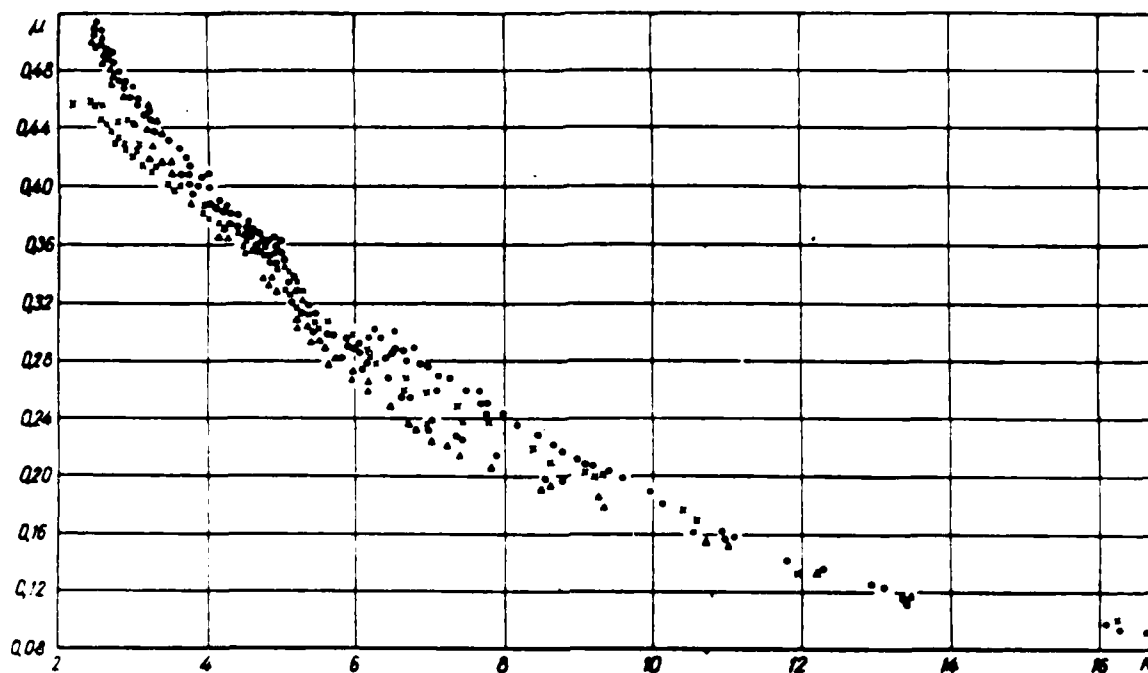


Fig. 4. Rotational effect to value of coefficient of flow rate μ (rounded entering edge of opening/aperture). Value of rounding $\times - \frac{r}{d} = 0.02$, $\circ - \frac{r}{d} = 0.06$, $\Delta - \frac{r}{d} = 0.08$. \bullet -- sharp entering edge. Diameter of opening/aperture 25 mm.

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As it follows from examination of dependences, given in Fig. 3, for all openings/apertures with sharp entering edge coefficient of flow rate decreases with increase in relative peripheral speed of at first fitting (to $u/C_0=2.5$, which corresponds approximately $\mu=0.3$), and then curve flows/occurs more gently. In this case the absolute values of the coefficient of flow rate with an increase in parameter K , to 6 decrease approximately 6-7 times. This corresponds to an increase of the drag coefficient 35-40 times. It is completely obvious that the neglect during calculations by a change in the coefficients indicated is completely inadmissible.

Following set of experiments was dedicated to study of effect of radius of bending of intake edge on coefficient of flow rate for rotating openings/apertures. Experiments were conducted on the opening/aperture with a diameter of 25.0 mm, whose trailing edges remained sharp/acute. The radii of bending of entering edges for the

openings/apertures were selected in the limits of 0.5-2.0 mm, which corresponds to a change in ratio r/d for the opening/aperture from 0.02 to 0.08. The results of experiments given in Fig. 4 make it possible to make the conclusion that the absolute values of the coefficients of flow rate for the openings/apertures with the sharp and chamfered edges little (to 10-12%) differ from each other. With a sufficient degree of accuracy the equations given above can be used for determining the coefficients higher than equation they can be used for determining the drag coefficients and flow rate of openings/apertures with any form of entering edge. This phenomenon sufficiently well will agree with the theoretical analysis. From literature data it is known that the total coefficient of the hydraulic resistance of channel with a length of 2-10 diameters with the sharp entering edges composes approximately 1.55, and with those strongly rounded - 1.05, which produces the appropriate change in the coefficient of flow rate from 0.8 to 0.97, i.e., approximately to 20%. Since during the rotation of disk the coefficient of flow rate decreases 6-7 times, the effect of entering edges conceals itself. The obtained results make it possible to assume that an increase in the losses rotation is caused mainly by the deviation of the direction of the rates of entry and output/yield from the axis/axle of channel, i.e., during the rotation takes place of the intense "impact/shock" in the intake part of the openings/apertures. For checking this assumption the flow through the openings/apertures, situated at angle to the lateral surfaces of disk, one should conduct research.

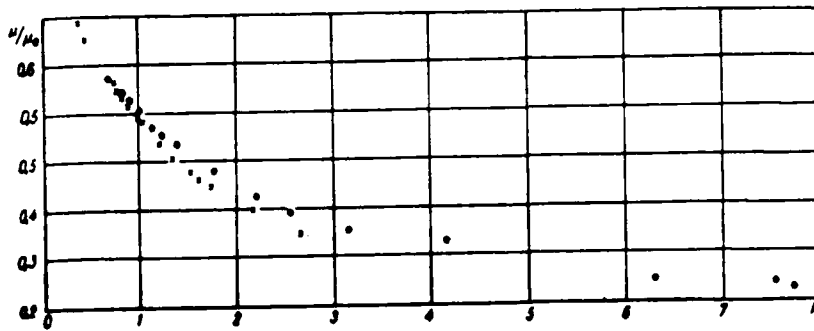


Fig. 5. Rotational effect to coefficient of flow rate μ (rounded trailing edge of opening/aperture). \bullet - sharp trailing edge, \times - rounded trailing edge, $r/d=0.35$.

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Third set of experiments was dedicated to study of effect of rounding of trailing edges on air flow through openings/apertures in rotary disks. Experiments were conducted on the openings/apertures with a diameter of 14.3 mm, which had the constant (sharp) entering edge. The trailing edge of opening/aperture, during the first experiment which was being fulfilled by sharp/acute, was rounded by a radius of 5 mm, which corresponds to ratio $r/d=0.35$. The results of these tests are represented for Fig. 5, from which it follows that the configuration of trailing edges does not exert a substantial influence on the conditions for air flow through the openings/apertures in the rotary disks and in practical computations it can be disregarded. The fourth set of experiments had by its purpose a study of the effect of the form of channel on the conditions for air flow through the openings/apertures in the rotary disks. Fig. 6 gives the results of experiments on the study of air flow through the square and round

channels with the equivalent hydraulic diameter. The comparison of the results, obtained with the blasting of square and cylindrical channels with the identical hydraulic diameters, shows that the form of cross section has a weak effect on a change in the coefficient of flow rate during the rotation (maximum disagreement of experimental data of order 3%). The limited volume of experiments for the openings/apertures of various forms does not make it possible, however, to consider this conclusion universal. It can seem that for the channels, in the form of the flow area of those differing from the square (for example, for the narrow rectangular slots), the disagreement will be more essential, that it requires supplementary experimental investigation.

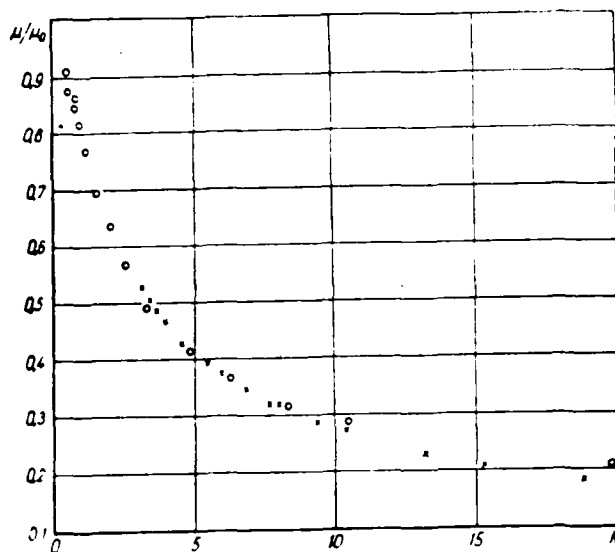


Fig. 6. Rotational effect to value of coefficient of flow rate μ with various forms of channel. \times - square opening/aperture. o - cylindrical opening/aperture.

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Conclusions/derivations.

1. Rotation of disk exerts a substantial influence on condition of course of air through openings/apertures. In the large ratios of the velocity of the rotation κ of the mean flow rate in the opening/aperture (order $u/c=2.5$) the value of the coefficient of flow rate for the openings/apertures with the sharp entering edges decreases approximately 6 times.

2. With sufficiently high u/c (more than than 4) effect of form of entering edges it is possible not to consider.

3. Rounding of trailing edges virtually does not have effect on conditions for air flow through openings/apertures in rotary disks.

4. Coefficient of flow rate of openings/apertures of square form investigated in work is close to coefficient of expenditure of cylindrical channels (with identical hydraulic radii).

5. Relative depth of opening/aperture in the range of relations $0.96 < \frac{l}{d} < 6.04$ virtually does not have effect on dependence of value of coefficient of flow rate from rotation.

6. On the basis of analysis of experimental data in work empirical dependence of coefficients of flow rate and hydraulic resistance on parameters K and K_0 are obtained. The relationships/ratios indicated are valid for the disk, which rotates in the housing with the value relative to the axial clearance between the disk and the housing of more than 1.5.

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2. B. I. Morozov. Experimental investigation of flows in the step/stage. Transactions of MEI, V. 28, Gosenergoizdat, 1956.

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